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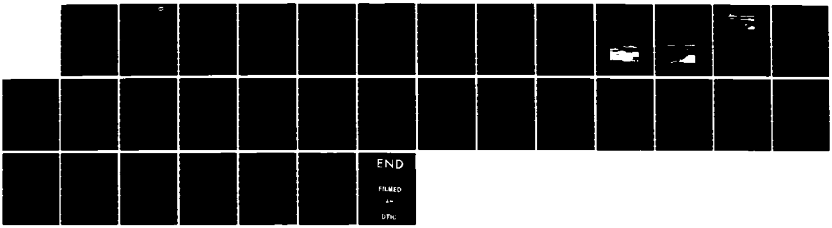

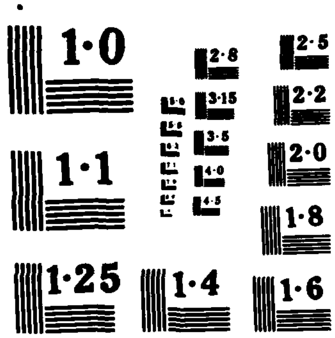


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# *Determining the effectiveness of a navigable ice boom*

Roscoe E. Perham







Prepared for
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The performance of a navigable ice boom was studied by monitoring the progression of the leading edge of the unconsolidated ice cover over a reach of the St. Marys River directly downstream of the boom. Ice and hydraulic data were obtained for four winters from 1975-76 through 1978-79 for the St. Marys River at Sault Ste. Marie, Michigan. The ice cover progression rate was highest in early winter. The unconsolidated ice cover in the channel was estimated to have a thickness of at least 0.91 m and a porosity of 30%. During early winter the ice discharge per vessel passage averaged approximately 5500 $m^3$

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for the four years. Model tests for this site had indicated that without an ice control structure of any type, an ice release of 63,000 $m^3$ per ship passage could be expected; with an ice boom the release would be 12,300 $m^3$ per ship passage. If a 100% effective boom releases no ice at all, then the measured rate indicates that the boom is 92% effective. On-site observations and time-lapse movies provided partial verification. Ice flowed down the ship track and through the navigation opening fairly often. Occasionally ice came over the boom in response to ship movements and natural causes.

## PREFACE

This report was prepared by Roscoe E. Perham, Mechanical Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

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# DETERMINING THE EFFECTIVENESS OF A NAVIGABLE ICE BOOM

Roscoe E. Perham

## INTRODUCTION

A variety of ice problems were encountered in the St. Marys River due to winter navigation. To minimize ice accumulation problems, a floating timber ice boom was installed at the outlet of Soo Harbor, at Sault Ste Marie, Michigan, leading into the 183-m-wide and 9.1-m-deep Little Rapids Channel. The 76-m-wide navigable opening of the boom is centered on the navigation course number 2 shown in Figure 1. The location of the ice boom and the size of the opening were selected after a study of various ice control arrangements in a physical model (Cowley et al. 1977). The structure was considered to be fully successful because the required river water levels and flows could be maintained during the entire winter.

The model study developed a measure of the effectiveness of an ice control structure. A simulated ice cover made of plastic pellets weakly bonded together was constructed on the 1:120 scale model. The pellet size was equivalent to a full-scale ice thickness of 0.3 m. A self-propelled model ship was piloted through the cover by remote control. The ice discharge from the harbor was collected downstream and measured. The average quantity of ice released per vessel passage for natural conditions was the equivalent of 63,000 $m^3$ per ship passage. The model ice control structure decreased this value to the equivalent of 12,300 $m^3$ (434,000 $ft^3$) per ship passage, or about 20% of the uncontrolled value. The model control structure, therefore, had an effectiveness of 80% for reducing the ice discharge per vessel passage.

Determining the ice discharge through and over an ice boom is much more difficult in the field because the ice cannot be measured easily or safely. The primary method used by the Detroit District, U.S. Army Corps of Engineers (1979) was to monitor the ice movements near the boom by time-

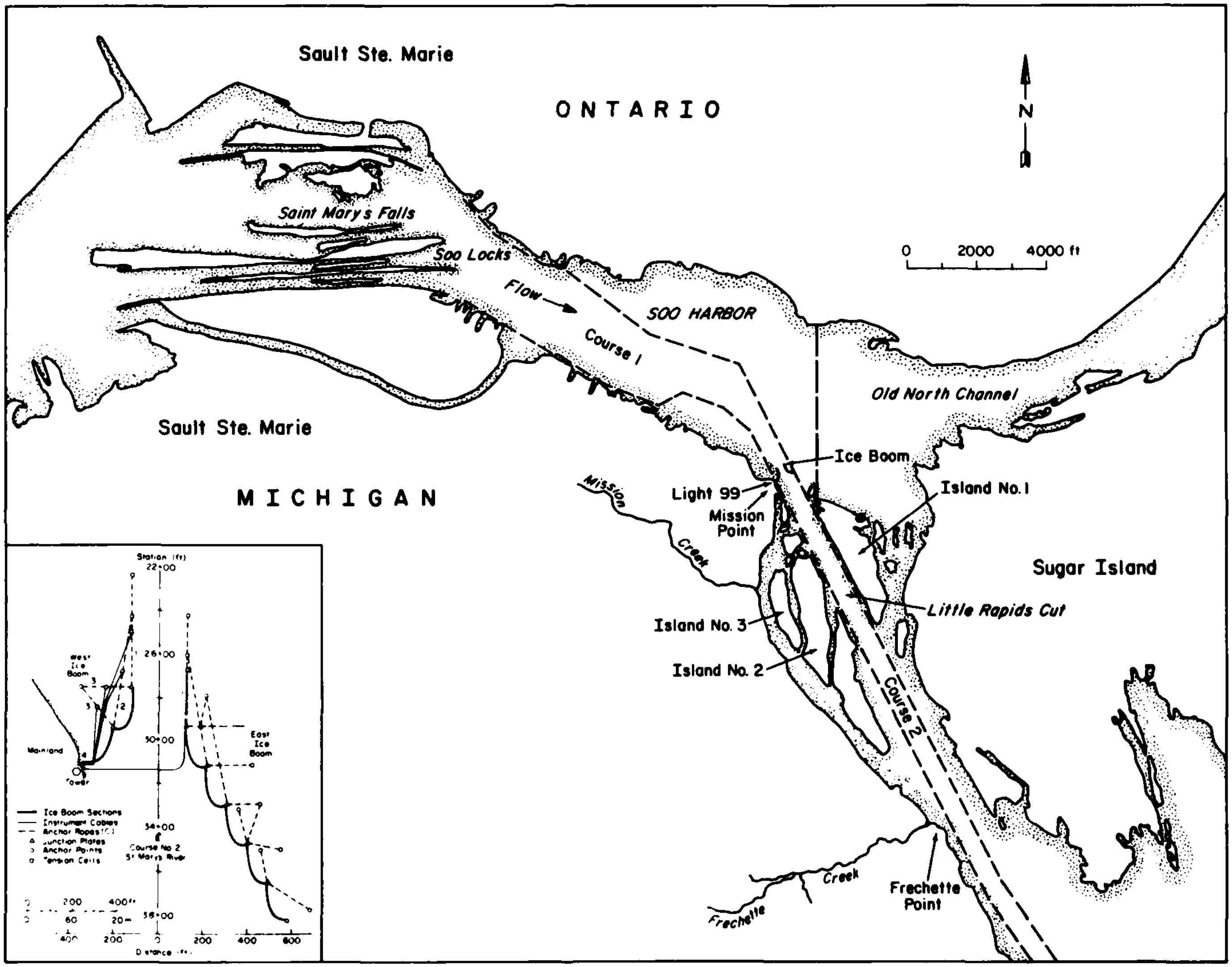



Figure 1. Soo Harbor and Little Rapids Channel.

lapse movie camera and estimate ice quantities from the record. For additional documentation, oblique photographs were taken of the St. Marys River on a weekly basis.

For the present study, however, the ice discharge was determined by observing the location of the upstream edge of the unconsolidated ice cover in a reach of the Little Rapids Channel having a fairly constant cross-sectional area. It was assumed that a unit movement of the ice edge is caused by a particular quantity of ice coming from Soo Harbor. This report provides the ice edge data and discusses its accuracy and merits compared to the time-lapse information. Unconsolidated ice thickness measurements and ice growth in the area are also discussed.

## Soo Harbor

Soo Harbor is quite large and is irregularly shaped on the Canadian side (Fig. 1). Its area is approximately $3.7 \times 10^6$ m$^2$ ($40 \times 10^6$ ft$^2$). The St. Marys Falls reach is generally open water for most of the winter and has an area of about $0.6\text{-}0.7 \times 10^6$ m$^2$ ($6\text{-}7 \times 10^6$ ft$^2$). The opposite (eastern) limit of the harbor for the purposes of this study is a line leading due north from the ferry dock at Sugar Island to the Canadian shore.

Two areas in Soo Harbor remain ice free throughout the winter: the St. Marys Falls downstream of the three hydroelectric plants and a thermal outfall of the Algoma steel plant in the northwest corner of the harbor. The most complete ice cover seen was approximately $3.3 \times 10^6$ m$^2$ ($35 \times 10^6$ ft$^2$), or 88% of the harbor. The harbor was usually considered to be fully ice covered, however, when the ice area was smaller, because ship activity and atmospheric disturbances could keep the size of these areas changing by 10% or so. For instance the area of the 4.1-km-long ship track was approximately $0.13 \times 10^6$ m$^2$ ($1.4 \times 10^6$ ft$^2$). Sometimes the track is covered with ice and sometimes it isn't.

Table 1. Date of complete ice cover on Soo Harbor.

| Winter | Ice cover complete | Ice cover stable | Ice thickness above west boom (m) |
|---|---|---|---|
| 1975-76 | 15 January | 22 January | ? -0.13 |
| 1976-77 | 28 December | 29 December | 0.13 |
| 1977-78 | 10 January | 11 January | 0.18 |
| 1978-79 | 7 January | 8 January | 0.18-0.30 |

Table 1 gives the dates when Soo Harbor was frozen over and the dates when the complete ice cover appeared stable. The term "stable ice cover" for the harbor area means that the overall ice cover dimensions remained the same, even though much of the cover was fragmented.

## Little Rapids Channel

The Little Rapids Channel (Fig. 2) is a man-made navigation improvement connecting Soo Harbor with Lake Nicolet. It has a 183-m- (600-ft-) wide channel excavated to a minimum depth of 8.2 m (27 ft). The narrowest portion of the channel is at its upper end, where Island No. 1 was cut in two. This part of the channel has a cross-sectional area of 1609.8 $m^2$ (17,327.4 $ft^2$) at a low water datum elevation of 176.05 m (577.6 ft) and reaches from the upper end of Island No. 1 approximately to navigation light 95, a distance of 1500 m (5000 ft). This cross-sectional area is approximately the same for 250 m (820 ft) or so above and below these points. The natural width of the reach between Island No. 4 and Frechette Point is greater than that at Frechette Point. How this convergence affects the flow is unknown. The cross-sectional flow area at Frechette Point is 2407.3 $m^2$ (25,912.4 $ft^2$) at a low water datum of 176.02 m (577.5 ft). The ratio of the Little Rapids Cut area to the Frechette Point area is 0.67. One would expect, therefore, that the flow velocities in the


Figure 2. Little Rapids Channel.

upper half of the channel would be roughly 50% higher than those in the lower half. Further details of the channel are given in Appendix A.

## DATA COLLECTION AND ANALYSIS

### Ice Edge Progression

The water velocity in the Little Rapids Channel is too high for an ice cover to grow across it from shore to shore. Instead an ice cover must first form downstream in the lower velocity reaches of Lake Nicolet and bridge across the channel about 3.5 km (2.2 miles) below the ice boom. The ice floes, brash ice and frazil slush moving downstream are stopped by this ice bridge, and the incoming ice causes the leading ice edge to progress upstream. The ice entering the channel usually comes down the shipping track as brash and slush ice, but sometimes it moves over the boom as broken sheets. Examples of these types of ice at the navigation opening are shown in Figure 3. The ice movements are triggered primarily by wind and ship activity and occasionally by water level fluctuations.

During the first winter of ice boom operation, 1975-76, my efforts were concentrated on measuring forces on the boom (Perham 1977), but I also attempted to estimate the area of the ice cover in Soo Harbor and Little

a. Ice floes generated by a passing ship.

Figure 3. Moving ice at the boom opening.

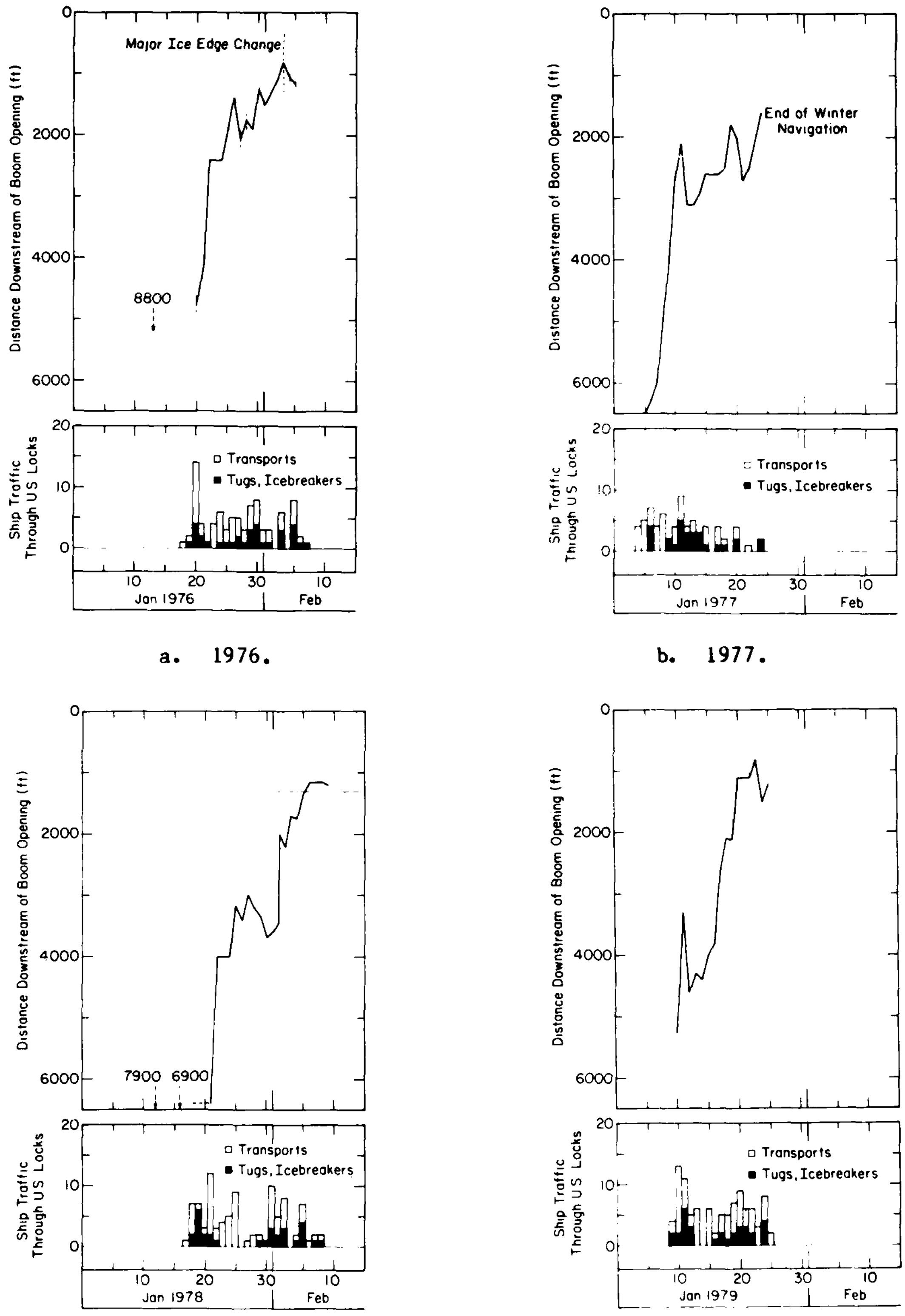
b. Brash ice and ice floes mixed with slush accumulations. The flow is from left to right.

Figure 3 (cont'd). Moving ice at the boom opening.

Rapids Channel. From light tower 99 at Mission Point, one can see up to the Soo Locks and down the Little Rapids Channel to Frechette Point 3.5 km (2.2 mi) away. To help quantify ice coverage in the harbor and the channel, a map of the channel approximately 1.2 km upstream and downstream of the boom was made. Station markers were installed at 152-m (500-ft) intervals along the Sugar Island side of Little Rapids Channel. Sketches of ice coverage were made on the maps on a regular basis and at the same time the location of the ice edge in Little Rapids Channel was noted. Some data were also available from oblique aerial photographs acquired by the Detroit District (Fig. 2).

It was hoped at first that the ice edge location could be monitored the full distance from Frechette Point to the ice boom, but a careful look at the data showed several inconsistencies at points that far away. The data from near the lower end of Island No. 4 to the ice boom, however, were reasonably good.

The progression of the ice edge in the Little Rapids Channel was monitored for four years (Appendix A), and the data are plotted in Figure 4. Data were taken visually by observers. The curves are jagged once the ice edge nears the ferry track; this is almost exclusively due to ice-breaker activity.




a. 1976.

b. 1977.

c. 1978.

d. 1979.

Figure 4. Progression of the ice edge in Little Rapids Channel.

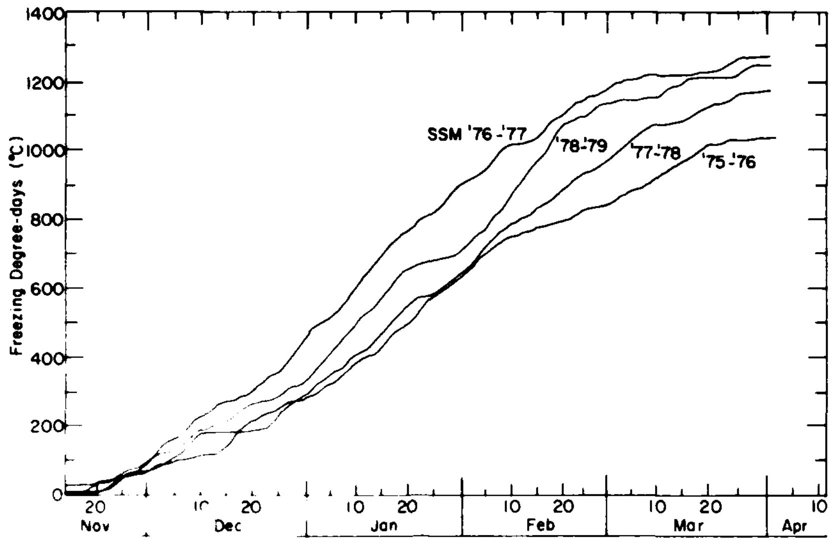



Figure 5. Freezing degree-days at Sault Ste. Marie.

There are fairly obvious trends in these curves. The early portion of each curve is very steep, showing that the ice edge had moved rapidly. During this period the air temperatures remained fairly constant, but of course they varied from one year to the next. The highest temperature was -8.6°C, during the winter of 1977-78, and the lowest was -19°C, during 1976-77; the average for the four years was -15°C. Curves of degree-days of freezing for the four winters are in Figure 5. As the ice edge approached the ferry track, its upstream progress would slow. This may have been due to a reduction in the rate at which ice arrived at the ice edge but it was also due to the action of ice breakers and ships. Later in the winter the ice edge location would move upstream and downstream while generally moving slowly away from the ferry track. At the time of spring ice breakup, the ice edge moved quickly downstream.

The rate of ice edge progression can be determined from the slope of the ice edge location and time curve. The most important factor, though, is how this affects ice volume, because the final determination of effectiveness in this situation is the ratio of the ice volume to the number of ship passages. To determine ice volumes, one must know the depth and porosity of ice in the unconsolidated ice cover.

<u>Unconsolidated ice cover thickness</u>

Very few measurements of ice thickness have been made in the Little Rapids Channel. During the second week of February 1974, Voelker and Friel

(1974) obtained values at various cross sections from 270 to 1130 m below the ice boom location. This was done after shipping stopped for the winter and is an example of pre-ice-boom conditions. The thicknesses varied widely but averaged between 1.2 and 2.0 m. Ships required ice breaker assistance at times during the 1974 winter navigation season in order to transit the Little Rapids Channel. The substantial thicknesses are probably due more to ice breaker and ship action than to flow effects on the unconsolidated ice cover. Working from a boat in 1979, I found the thickness of the ice edge near the ferry track following a period of typical ship activity to average 0.92 m (3 ft). Ship passages for the previous week were 10 upbound and 13 downbound transports and 6 upbound and 6 downbound U.S. icebreakers and work boats.

On 17 February 1978, Corps of Engineers personnel attempted to measure the discharge across a section of the channel at Frechette Point but could complete only three of seven stations due to the extremely difficult ice conditions. The ice thickness profile at that time indicated that approximately 15% of the total cross sectional area of the channel was filled with a combination of fixed and rafted ice. This value is equivalent to an average ice thickness of 0.90 m.

On the 23 and 24 February 1979, ice thickness was again measured by Corps personnel at Frechette Point, and these measurements showed substantial differences over the section. The ice was thicker at the edges of the ship track but had only a 1.22-m maximum. The minimum thickness of 0.15 m was in the approximate center of the ship track. The average ice thickness was 0.52 m. There were similar variations in measurements obtained on 8 and 10 February 1972 by the Corps, but the average thickness then was 0.91 m.

Vance (1980) measured brash ice thicknesses in the ship track farther downstream in the Middle Neebish Channel and in Lake Nicolet. He measured thicknesses from 1.07 to 1.52 m near Stribling Point, where the flow area varies from 2260 to 2940 $m^2$. On Lake Nicolet, where the flow area is as great as 11,000 $m^2$, the brash ice in the channel was 1.22 m thick and the solid ice thickness was 0.67 m. These findings show how ship transits as well as flow velocities lead to a thickening of the unconsolidated ice masses.

Because of the shortage of data on ice thicknesses in the Little Rapids Channel, I estimated the ice thicknesses using the theories described in the Appendix B. The ice thickness was estimated to be approximately 0.91 m or greater in Little Rapids Cut. It was assumed that the unconsolidated ice cover has a porosity of 30%, which is a rough estimate based on studies by Sandkvist (1981) and personal observations in other areas.

Table 2. Daily ship traffic through the U.S. Locks, upbound and downbound totals, during the period of major ice edge movement in Little Rapids Cut for four winters.

| | 1975-1976 | | 1976-1977 | | 1977-1978 | | 1978-1979 | |
|---|---|---|---|---|---|---|---|---|
| | Transports | Tugs, icebreakers | Transports | Tugs, icebreakers | Transports | Tugs, icebreakers | Transports | Tugs, icebreakers |
| Jan 4 | | | 4 | 0 | | | | |
| 5 | | | 5 | 0 | | | | |
| 6 | | | 3 | 4 | | | | |
| 7 | | | 4 | 0 | | | | |
| 8 | | | 6 | 0 | | | | |
| 9 | | | 0 | 2 | | | 2 | 2 |
| 10 | | | 3 | 1 | | | 11 | 2 |
| 11 | | | 4 | 5 | | | 5 | 6 |
| 12 | | | 1 | 3 | | | 2 | 3 |
| 13 | | | 2 | 3 | | | 6 | 0 |
| 14 | | | 0 | 3 | | | 0 | 0 |
| 15 | | | 3 | 1 | | | 6 | 0 |
| 16 | | | 0 | 0 | | | 1 | 1 |
| 17 | | | 3 | 1 | 1 | 0 | 3 | 2 |
| 18 | 1 | 0 | 1 | 1 | 5 | 2 | 4 | 1 |
| 19 | 1 | 1 | 0 | 0 | 1 | 6 | 5 | 2 |
| 20 | 10 | 4 | 2 | 2 | 1 | 2 | 6 | 3 |
| 21 | 2 | 2 | 0 | 0 | 10 | 2 | 3 | 3 |
| 22 | 0 | 1 | 1 | 0 | 2 | 1 | 4 | 2 |
| 23 | 4 | 0 | 0 | 0 | 4 | 0 | 3 | 0 |
| 24 | 5 | 1 | 0 | 2 | 5 | 0 | 4 | 4 |
| 25 | 2 | 1 | | | 9 | 0 | 2 | 0 |
| 26 | 4 | 1 | | | 0 | 0 | | |
| 27 | 3 | 2 | | | 0 | 0 | | |
| 28 | 2 | 1 | | | 1 | 0 | | |
| 29 | 4 | 3 | | | 2 | 0 | | |
| 30 | 4 | 4 | | | 1 | 1 | | |
| 31 | 2 | 1 | | | 0 | 1 | | |
| Feb 1 | 2 | 1 | | | 7 | 3 | | |
| 2 | 0 | 0 | | | 3 | 2 | | |
| 3 | 3 | 3 | | | 5 | 3 | | |
| 4 | 0 | 0 | | | 0 | 0 | | |
| 5 | 4 | 4 | | | 1 | 1 | | |
| 6 | 1 | 1 | | | 3 | 4 | | |
| 7 | 0 | 1 | | | 1 | 0 | | |
| 8 | 4 | 2 | | | 1 | 1 | | |

## Ship Traffic

The source of information about ship traffic is the logbook for the U.S. locks operated by the U.S. Army Corps of Engineers, Soo Area Office. I have grouped ships into two categories: transports, which vary considerably in size and power, and icebreakers and tugs or work boats. The transport ships have the greatest effect on the Soo Harbor ice cover, and at times they need to have an icebreaking tug assist them, particularly at the angle bend between course 1 and course 2.

The transports varied from 99 m long x 15 m wide (324 x 49 ft) to 305 x 32 m (1000 x 105 ft); the average length was about 213 m (700 ft). The transports were mainly iron ore carriers, but there were occasional fuel carriers (Perham 1984).

Most of the ship lockages resulted in a transport passing through the boom, but occasionally one stayed in the harbor. Most ships transited the boom on the same day that they locked through, but some did not. Keeping track of the icebreakers and tugs is quite difficult because they could pass through the navigation opening several times without having to go through the locks. In any case the main contributor to ice losses from Soo Harbor was the transport ships, and the ice losses are considered to be related solely to their passages. Table 2 lists the number of ship lockages per day during the periods of rapid ice edge progression for each of the four winters. The quantities are also plotted in Figure 4.

## Ice discharge per ship

The ice discharge per ship is calculated by converting the change in location of the ice edge to an equivalent value of ice quantity and dividing that value by the number of transport ship passages in the period during which the location changes took place. Figure 4 shows that the ice edge sometimes progressed upstream very rapidly, sometimes remained stationary, and occasonally moved downstream. The downstream movement was probably due to transport and icebreaker activity (especially the latter), but sometimes an unconsolidated ice cover will collapse or telescope by itself and become thicker, enabling it to withstand the flow forces. At times icebreakers have worked the full length and breadth of Little Rapids Cut with the same effect. It is not possible to say exactly what caused the ice edge recession or apparent inactivity.

Table 3. Calculated values of ice discharge per ship passage based on ice edge progression in Little Rapids Cut.

| Winter | Period | Selected dates | Location of the edge (ft) | Location of the edge (m) | Number* of ships | Ice discharge per ship ($ft^3$) | Ice discharge per ship ($m^3$) |
|---|---|---|---|---|---|---|---|
| 1975-76 | IEP† and Dominant | 20 Jan<br>26 Jan | 4750<br>1400 | 1448<br>427 | 23-1/2 | 180,000 | 5,090 |
| | | 20 Jan<br>22 Jan | 4750<br>2400 | 1448<br>732 | 12 | 247,000 | 6,990 |
| | | 21 Jan<br>26 Jan | 4100<br>1400 | 1250<br>427 | 14 | 243,000 | 6,880 |
| | | 21 Jan<br>22 Jan | 4100<br>2400 | 1250<br>732 | 2** | 1,071,000 | 30,300 |
| 1976-77 | IEP and Dominant | 5 Jan<br>11 Jan | 6500<br>2100 | 1981<br>640 | 20-1/2 | 270,000 | 7,660 |
| | | 7 Jan<br>11 Jan | 6000<br>2100 | 1829<br>640 | 13 | 378,000 | 10,700 |
| 1977-78 | IEP | 20 Jan<br>5 Feb | 6400<br>1350 | 1951<br>411 | 50 | 127,100 | 3,600 |
| | | 21 Jan<br>22 Jan | 6400<br>4000 | 1951<br>1219 | 10** | 302,000 | 8,560 |
| | | 31 Jan<br>3 Feb | 3600<br>1700 | 1097<br>518 | 11-1/2 | 208,000 | 5,900 |
| | Dominant | 20 Jan<br>27 Jan | 6400<br>3000 | 1951<br>914 | 30-1/2 | 140,000 | 3,980 |
| 1978-79 | IEP | 10 Jan<br>20 Jan | 5250<br>1100 | 1600<br>335 | 40-1/2 | 129,000 | 3,650 |
| | | 10 Jan<br>11 Jan | 5250<br>3300 | 1600<br>1006 | 8 | 307,000 | 8,700 |
| | Dominant | 14 Jan<br>20 Jan | 4400<br>1100 | 1341<br>335 | 22 | 189,000 | 5,400 |

* Includes average of number of passages on first and last days of period, which can yield values of 1/2 ship.
† Ice edge progression period.
** Estimated maximum, 1 ship fewer is a possibility.

There are brief periods when the ice discharge per ship is higher than the average for a longer period of time. It is thought that these higher values are a real effect and are the upper limit for the ice control system. Ordinarily, average values for longer periods of time are more credible than short-term values, but this may not be the best way to interpret the present results.

Table 3 contains values of ice discharge for the four winters. These data were analyzed in several ways. An ice edge progression period (IEP) was selected to include most of the times when the ice edge moved rapidly upstream in the cut. In addition, a dominant period was designated to represent a period of time that included a significant amount of ice movement and a significant number of ship passages. The remaining periods shown in Table 3 are shorter and generally represent the most rapid ice edge progressions. Unless otherwise indicated, the total number of ships for a period includes an average of ship passages on the first and the last day of a period. The reason for this is that ships passing late in the day would not have influenced the ice edge location established for that day. This averaging sometimes yields values of 1/2 ship.

The last columns in Table 3 give the values for the ice discharge through the boom per transport ship passage. The dominant values vary from 3980 to 7660 $m^3$/ship and have a four-winter average of 5530 $m^3$/ship. These values, of course, are influenced by meteorological conditions, which can cause substantial ice movements. However, the ice cover is easier to move by wind and water currents after it is broken by the ships.

The maximum ice discharge for nondominant periods varied from 30,300 to 5,900 $m^3$/ship. Ignoring these values and taking the average of maximum ice discharge for the five remaining nondominant periods, a value of 8370 $m^3$/ship is obtained.

Other evidence

Time-lapse photography. An 8-mm movie that covered the ice edge progression period for the winter of 1978-79 was available. It shows the navigation opening and the ice cover above the booms including the ship track approximately up to the angle turn from course 2 to course 1. The film was exposed at a rate of 1 frame per 90 s and was viewed at 6 frames per s. It showed Soo Harbor exit conditions for approximately 8.5 hrs per day. During part of the movie, the view was obscured by "frost smoke" and snowfall.

The passages of large transport ships were easy to see, but those of Coast Guard vessels and work boats were not. From 10 to 24 January, 23 large vessels passed; in addition, there were about 16 small vessel transits. The vessels generally seemed to cause ice releases in proportion to their sizes. Not all vessels caused ice releases, but most transport ships

did during this period. These releases seemed to be typical ice runs containing slush ice, brash ice and ice floes (Fig. 3).

The average water velocity based on total river flows and previous under-ice water velocity measurements was 0.52 m/s (1.7 ft/s) in Soo Harbor. The speed of the ice run was assumed to be somewhat less, about 0.46 m/s (1.5 ft/s). The widest commercial vessels were 32 m (105 ft) wide, which controls the minimum width of the ship track, provided the ice sheet does not move laterally. An ice run rarely covered the whole width of the track, but it would often cover a third to a half of it. A typical ice run was estimated to be a mass 13 m (44 ft) wide and 0.13 m (0.43 ft) deep with a porosity of 50%. The length of time that it flowed was measured with a stopwatch from the movie and then converted to real time.

In addition to the ice moving in the ship track, a substantial quantity of ice moved over the boom as broken ice sheets. Some of this ice (measured from a work boat) was over 0.3 m thick. The volume of this ice was estimated from this thickness and the area that was seen to move over the west ice boom. Most of the sheet ice was released during the first week.

The total amount of ice released between 10 and 24 January was estimated to be $3.3 \times 10^6$ ft$^3$ ($9.3 \times 10^5$ m$^3$). For the 23 commercial ships that were seen to pass, the ice release was therefore 4060 m$^3$/ship ($1.6 \times 10^5$ ft$^3$/ship). Approximately 65% of this ice release went over the boom as solid sheet ice.

Ice Boom Logbook. A nearly continuous series of observations of ice runs in the ship track and ice movement over the booms were noted in the logbook kept at the ice boom site. These data were compared with those from the time-lapse photography, and they corroborated the photographic evidence: the logbook showed that the ice ran in the ship track for a total of 77,000 s, while the time-lapse movie showed that the ice ran for 80,000 s.

## DISCUSSION

### Ice generation in open water

A paradoxical situation exists in Little Rapids Cut. Heat transfer calculations show that enough ice could be generated in the open water there to nearly account for the ice edge progression rates. A value for water surface conductivity of 22.5 W/m$^2$·K is often used but may be high for

this location (Devik 1944, 1948). The ice grown in the open water of Little Rapids Cut is frazil slush in form and does not develop into ice pans with strength and appreciable buoyancy. The typical situation is illustrated in Figure 2, which shows the ice edge at the lower end of Island No. 4 on 18 January 1978. There was no wind and the air temperature was -23°C. The change in the water surface from glassy to rough is probably due to developing frazil flocs. The ice was very porous, probably 90% or higher, and for ice such as this to remain at the ice edge, the water velocity must be quite low. According to Michel (1971), for the existing water depth of 9.54 m, the average velocity should be 0.48 m/s or less for frazil slush to contribute directly to ice edge progression. The average open water velocity for 1978 was 0.77 m/s. The other average velocities varied from 0.60 to 0.69 m/s. Frazil and snow slush will therefore be drawn beneath the ice edge. Some of the slush could be trapped in pockets between the tilted ice floes and contribute in a minor way to the ice edge progression rate. However, most of the slush moves downstream beneath the unconsolidated ice cover to be deposited at various locations in the ice-covered channel and in Lake Nicolet. What happens to it is complex and will not be discussed here. Under certain circumstances these deposits can lead to flooding in Soo Harbor, but this did not happen during my study.

## Ice Thickness

The method described here for estimating the ice discharge is simple to implement and monitor. The main problem lies in determining the thickness and porosity of the unconsolidated ice cover that develops in the channel. The ice cover is unsafe to work on, so a radar system mounted on a helicopter is probably the best approach for measuring ice thickness. Ground truth measurements of ice thickness and brash ice sampling for determining porosity could be done safely from a work boat. In lieu of this, however, predicting ice thickness by theoretical means is acceptable. The methods in Appendix B are a conservative approach for estimating thickness.

## Comparison with Other Ice Inventories

The results of this study differ from the findings of Daly and Weiser (1981), which were based on a review of films from time-lapse cameras scanning the ice boom area. The quantities found here are greater by approximately an order of magnitude. I'm not sure why their results were so low,

especially in light of the ice inventory in the U.S. Army Corps of Engineers (1979) report.

The time-lapse movies were reviewed by Corps personnel at the Detroit District and were analyzed for a section in their annual report on Soo Harbor water levels for the 1977-1978 and 1978-1979 seasons. The inventory gave no quantities other than general descriptions. It indicated that ice moved fairly often due to the passage of ships, but no quantities were given for these events. The observations were by daylight only. There were ship passages and ice movements at night too, as indicated in the ice boom logbook. For example, on 14, 15 and 16 January 1979 the inventory had "extremely light" or "light" ice flow through the opening, yet the ice edge progressed from 1310 to 790 m (4300 to 2600 ft) below the boom. The logbook data, however, showed that several ships passed by on the nights of 15 and 16 January and caused considerable ice losses from the harbor.

Comparison with Model Tests

The full-scale conditions used by Cowley et al. (1977) in the 1:120 model were a river flow of 2435 $m^3/s$ (86,000 cfs) and an ice thickness of 0.3 m (1.0 ft). The model testing had turbulent flow in all of the navigation channels and beneath most of the ice cover.

One noticeable difference was the speed of the model ship, which was based on a full-scale speed of 1.3-2.2 m/s. The actual ship speeds varied from 0.85 to 5.6 m/s and averaged 3.7 m/s. This higher speed is bound to cause greater ice releases than lower speeds, but a detailed evaluation of this phenomenon is not possible. It is the larger ships that usually go faster through the ice. This effect could best be determined by model studies organized specifically for that purpose.

A second important difference was in the physical properties of the ice. The model ice cover remained broken after the model ship passed through; that is, it could not refreeze. Also, the model ice material, polyethylene, did not have the same cohesive properties as ice. However, since the material was in small pellets, the surface tension effects of the water may have simulated cohesion to some extent. Cowley et al. (1977) did not indicate that this effect was studied; instead, the observations concentrated on the larger fracture patterns and ice floe development. In addition, model ice was added to the model after each ship passage, but no thermodynamic correlation was given for the quantity used.

Cowley et al. (1977) operated their model ship so that it would break out more ice than they thought the normal ship operations would. However, full-scale ship operations often break out more ice than is necessary, for example, to get ships from Little Rapids Cut to the locks. Docks on both sides of the harbor were used fairly often and work boats were often seen widening the shiptrack. The model study, then, simulated the actual conditions fairly accurately.

The harbor ice cover was further stabilized by structures set in place two years after the ice booms were installed (Perham 1984). No attempt was made, however, to optimize the location or the type of structure used.

## Ice Cover in Soo Harbor

Thermal effluents in the area reduce the thickness of the ice cover at various locations in Soo Harbor. They affect ice conditions in the Little Rapids Channel as well, but no data were obtained on this subject. Conceivably the quantity of heat input could vary appreciably from one day to another.

The thickness of the ice sheet in Soo Harbor was an important factor in the stability of the ice cover behind the boom. In early winter the thin ice sheets were easily broken by wind and wave effects and by water surface variations due to passing ships and river flow changes. The rather small pieces that were created easily moved out into ship track and down through the ice boom opening. Later, as the ice grew to over 0.3 m thick, it become more resistant to breaks, and when breaks occurred, the sections that formed were large and often unable to move into the ship track. The periods of rapid ice progression in Little Rapids Channel invariably occurred in early winter, when the harbor ice was relatively unstable.

## Non-dimensional Parameter

Calkins and Ashton (1975) conducted a model study of the arching of ice floes at a boom opening in a small hydraulic flume using two sizes of square plastic blocks as the model ice. In addition to block size, the variables were opening size, water velocity, and areal concentration of the blocks. The blocks were fed mechanically onto the water surface upstream of the boom opening. The blocks would eventually arch across the opening and prevent more blocks from passing through.

As part of the test the researcher would break the arch mechanically, measure the time it took for the arch to reform, and measure the area of

the model ice released through the opening. The volume of ice released in these tests was proportional to the area because the ice thickness was constant. Calkins and Ashton presented the ice releases in non-dimensional form as $A_r/b^2$, where $A_r$ is the ice released per disturbance, and b is the opening size. They found that, on the average, $A_r$ was equivalent to $b^2$, or $A_r/b^2 \approx 1.0$ (Fig. 6). The results from other model studies are given in Table 4.

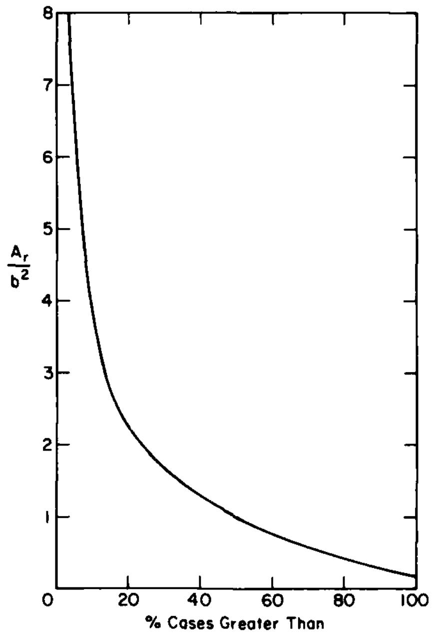



Figure 6. Area of ice released after disturbance of an arch. (After Calkins and Ashton 1975.)

Table 4. Values of $A_r/b^2$ for hydraulic navigation model studies.

| Reference | Opening size, b (m) | (ft) | $A_r/b^2$ |
|---|---|---|---|
| Acres American, Inc (1975) | 76 | 250 | 6 |
| Boulanger et al. (1975) | 76 | 250 | 4 |
| Arctec, Inc. (1978) | 69 | 225 | 3.5 |
| Arctec, Inc. (1980) | 69 | 225 | 2.7 |

A rough estimate of values for this parameter for the St. Marys River ice boom opening can be determined from the time-lapse photographs. They showed that $2.0 \times 10^5$ m$^2$ ($2.1 \times 10^6$ ft$^2$) of sheet ice and $4.9 \times 10^5$ m$^2$ ($5.3 \times 10^6$ ft$^2$) of brash and slush ice moved through the area. Twenty three commercial ships transited the opening during the period of movement; therefore $A_r/b^2 \approx 5$. However, sheet ice and brash and slush ice have quite different thicknesses and porosities. Converting the brash and slush area to an equivalent solid area before adding these together gives $A_r/b^2 \approx 2$.

This parameter can be calculated from the ice edge progression in Little Rapids Channel, but without much certainty. If the ice passing the boom is 0.3 m (1.0 ft) thick and has a porosity of 30%, the values of $A_r/b^2$ are 2.9, 4.3, 2.2 and 3.0 for the four winters studied. These values correlate well with model tests. The best type of information would have been the area and volumes of ice passing the boom. However, the problem of calculating the area of the mix of ice floes, brash ice and slush ice would remain.

## CONCLUSIONS

1. The effectiveness of the navigation ice boom at the head of Little Rapids Channel is substantially higher than predicted by the model study; i.e., average values of 5,500 to 8,400 m$^3$ per ship were found in early winter compared with the 12,300 m$^3$ per ship from the model study. Ice cohesion appears to be a major cause of this difference; there are several other factors that were not studied.

2. The equipment and techniques for measuring ice movements and accumulations need to be improved in order to quantify ice boom effectiveness.

## RECOMMENDATIONS

1. In further programs of this nature, a researcher or specially trained observer should be on site during the ice cover formation and stabilization periods to estimate the quantitites of ice released by passing ships. He should have assistance and equipment for determining ice thicknesses and porosities of brash and slush ice and of the unconsolidated ice cover.

2. The effects of thermal effluents should be evaluated to a reasonable extent for Little Rapids Channel.

3. A better method should be developed for measuring the amount of ice beneath the ice cover in Little Rapids Channel and in Upper Lake Nicolet.

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## APPENDIX A. LOCATION OF THE ICE EDGE IN LITTLE RAPIDS CHANNEL FOR FOUR WINTERS.

| 1975-1976 | | 1976-1977 | | 1977-1978 | | 1978-1979 | |
|---|---|---|---|---|---|---|---|
| Date | Location (ft) | Date | Location (ft) | Date | Location (ft) | Date | Location (ft) |
| 13 Jan 76 | 8800 | 29 Dec 76 | 11600 | 12 Jan 78 | 7900 | 9 Jan 79 | 11600 |
| | | | | | | 10 Jan 79 | 5300 |
| 20 Jan 76 a.m. | 4900 | 30 Dec 77 | 8000 | 16 Jan 78 | 6900 | 11 Jan 79 | 3300 |
| | | | | 18 Jan 78 | 6400 | | |
| 20 Jan 76 p.m. | 4600 | 3 Jan 77 | 11600 | 21 Jan 78 | 6400 | 12 Jan 79 | 4600 |
| 21 Jan 76 | 4100 | 5 Jan 77 | 6500 | 22 Jan 78 | 4000 | 13 Jan 79 | 4300 |
| 22 Jan 76 | 2400 | 6 Jan 77 | 6300 | 23 Jan 78 | 4000 | 14 Jan 79 | 4400 |
| 23 Jan 76 | 2400 | 7 Jan 77 | 6000 | 24 Jan 78 | 4000 | 15 Jan 79 | 400[illegible] |
| 24 Jan 76 | 2400 | 8 Jan 77 | 5000 | 25 Jan 78 | 3350 | 16 Jan 79 | 380 |
| 25 Jan 76 | 1900 | 9 Jan 77 | 4000 | 26 Jan 78 | 3400 | 17 Jan 79 | 260 |
| 26 Jan 76 | 1400 | 10 Jan 77 | 2700 | 27 Jan 78 | 3000 | | |
| | | 11 Jan 77 | 2100 | 28 Jan 78 | 3200 | 18 Jan 79 a.m. | 260 |
| 27 Jan 76 a.m. | 1900 | 12 Jan 77 | 3100 | 29 Jan 78 | 3350 | 18 Jan 79 p.m. | 210[illegible] |
| 27 Jan 76 p.m. | 2200 | 13 Jan 77 | 3100 | 30 Jan 78 | 3700 | 19 Jan 79 | 2100 |
| 28 Jan 76 a.m. | 1600 | 14 Jan 77 | 2900 | 31 Jan 78 | 3600 | 20 Jan 79 a.m. | 900 |
| 28 Jan 76 p.m. | 1900 | 15 Jan 77 | 2600 | 1 Feb 78 a.m. | 3450 | 20 Jan 79 p.m. | 1300 |
| 29 Jan 76 | 1900 | 16 Jan 77 | 2600 | 1 Feb 78 p.m. | 2000 | 21 Jan 79 | 1100 |
| 30 Jan 76 a.m. | 1200 | 17 Jan 77 | 2600 | 2 Feb 78 | 2200 | 22 Jan 79 a.m. | 1000 |
| 30 Jan 76 p.m. | 1300 | 18 Jan 77 | 2500 | 3 Feb 78 | 1700 | 22 Jan 79 p.m. | 1200 |
| 31 Jan 76 | 1500 | 19 Jan 77 | 1800 | 5 Feb 78 a.m. | 1500 | 23 Jan 79 | 800 |
| 1 Feb 76 | 1300 | 20 Jan 77 | 1600 | 5 Feb 78 p.m. | 1200 | 24 Jan 79 | 1500 |
| 2 Feb 76 | 1100 | 21 Jan 77 | 2700 | 6 Feb 78 | 1150 | 25 Jan 79 | 1200 |
| 3 Feb 76 a.m. | 1300 | 22 Jan 77 | 2500 | 7 Feb 78 | 1150 | 26 Jan 79 | 1700 |
| | | 23 Jan 77 | 2000 | | | | |
| 3 Feb 76 p.m. | 300 | 24 Jan 77 | 1600 | 8 Feb 78 | 1150 | 28 Jan 79 | 1600 |
| | | | | | | 29 Jan 79 | 1000 |
| 4 Feb 76 a.m. | 1000 | 25 Jan 77 | 2100 | 10 Feb 78 a.m. | 1350 | 30 Jan 79 | 1200 |
| 4 Feb 76 p.m. | 1100 | 26 Jan 77 | 1600 | 10 Feb 78 p.m. | 1900 | 31 Jan 79 | 1100 |
| 5 Feb 76 a.m. | 1100 | 27 Jan 77 | 2100 | 11 Feb 78 a.m. | 1350 | 1 Feb 79 | 1000 |
| 5 Feb 76 p.m. | 1200 | 28 Jan 77 | 1900 | 11 Feb 78 p.m. | 1600 | 2 Feb 79 | 1100 |
| 6 Feb 76 | 900 | 31 Jan 77 | 1200 | 12 Feb 78 | 1200 | 3 Feb 79 | 1100 |
| 7 Feb 76 | 900 | 1 Feb 77 | 1600 | 13 Feb 78 | 1500 | 4 Feb 79 | 800 |
| 8 Feb 76 | 1100 | 2 Feb 77 | 1600 | 14 Feb 78 | 1500 | 5 Feb 79 | 1500 |
| 9 Feb 76 | 1300 | 3 Feb 77 | 1600 | 15 Feb 78 | 1400 | 6 Feb 79 a.m. | 600 |
| | | | | | | p.m. | 1300 |
| 10 Feb 76 | 1200 | 4 Feb 77 | 2400 | 16 Feb 78 | 1300 | 7 Feb 79 | 1300 |
| 11 Feb 76 | 1000 | 5 Feb 77 | 2500 | 17 Feb 78 | 1400 | 8 Feb 79 | 1300 |
| 12 Feb 76 | 1100 | 6 Feb 77 | 2600 | 18 Feb 78 | 1400 | 9 Feb 79 a.m. | 1000 |
| 13 Feb 76 | 1100 | 7 Feb 77 | 2300 | 19 Feb 78 | 1400 | 9 Feb 79 p.m. | 1700 |
| | | | | 20 Feb 78 a.m. | 600 | | |
| 14 Feb 76 | 1100 | 8 Feb 77 | 2300 | 20 Feb 78 p.m. | 1700 | 10 Feb 79 | 1800 |
| 15 Feb 76 | 1100 | 9 Feb 77 | 2400 | 21 Feb 78 a.m. | 1200 | 11 Feb 79 | 2200 |
| 16 Feb 76 | 1100 | 10 Feb 77 | 2400 | 21 Feb 78 p.m. | 1600 | 12 Feb 79 | 2000 |
| 17 Feb 76 | 1200 | 11 Feb 77 | 2600 | 22 Feb 78 | 1600 | 13 Feb 79 | 2000 |
| 18 Feb 76 | 1300 | 12 Feb 77 | 2600 | 23 Feb 78 a.m. | 1400 | 14 Feb 79 | 2000 |
| 19 Feb 76 | 1300 | 13 Feb 77 | 2600 | 23 Feb 78 p.m. | 1100 | 15 Feb 79 | 1100 |
| 20 Feb 76 | 1300 | 14 Feb 77 | 2600 | 24 Feb 78 | 1600 | 16 Feb 79 | 900 |
| 21 Feb 76 | 1600 | 15 Feb 77 | 2600 | 25 Feb 78 | 1600 | 17 Feb 79 | 900 |
| 22 Feb 76 | 1600 | 16 Feb 77 | 2300 | 26 Feb 78 | 1600 | 18 Feb 79 | 1000 |
| 23 Feb 76 | 1500 | 17 Feb 77 | 2600 | 27 Feb 78 | 1400 | 19 Feb 79 a.m. | 900 |
| 24 Feb 76 | 1400 | 18 Feb 77 | 2600 | 28 Feb 78 a.m. | 1400 | 19 feb 79 p.m. | 1100 |
| 25 Feb 76 a.m. | 1400 | 22 Feb 77 | 2300 | 28 Feb 78 p.m. | 1900 | 20 Feb 79 | 1100 |
| 25 Feb 76 p.m. | 1300 | 23 Feb 77 | 2000 | 1 Mar 78 a.m. | 1600 | 21 Feb 79 | 1000 |
| 26 Feb 76 | 1400 | 24 Feb 77 | 2400 | 1 Mar 78 p.m. | 1900 | 22 Feb 79 | 1300 |
| 27 Feb 76 | 1600 | 25 Feb 77 | 2600 | 2 Mar 78 | 1700 | 23 Feb 79 | 1000 |

| 1975-1976 | | 1976-1977 | | 1977-1978 | | 1978-1979 | |
|---|---|---|---|---|---|---|---|
| Date | Location (ft) | Date | Location (ft) | Date | Location (ft) | Date | Location (ft) |
| 28 Feb 76 | 1600 | 28 Feb 77 | 2600 | 3 Mar 78 a.m. | 1900 | 24 Feb 79 | 1100 |
| 29 Feb 76 | 1600 | 1 Mar 77 | 2200 | 3 Mar 78 p.m. | 2000 | 25 Feb 79 a.m. | 1200 |
| 1 Mar 76 | 1500 | 2 Mar 77 | 2000 | 4 Mar 78 a.m. | 1700 | 25 Feb 79 p.m. | 600 |
| 2 Mar 76 | 1700 | 3 Mar 77 | 2100 | 4 Mar 78 p.m. | 2000 | 26 Feb 79 | 800 |
| 3 Mar 76 | 1700 | 4 Mar 77 | 2100 | 5 Mar 78 | 2000 | 27 Feb 79 | 1000 |
| 4 Mar 76 | 2100 | 7 Mar 77 | 2600 | 6 Mar 78 | 1900 | 28 Feb 79 | 1000 |
| 5 Mar 76 | 1800 | 8 Mar 77 | 4100 | 7 Mar 78 | 2200 | 1 Mar 79 | 1200 |
| 6 Mar 76 | 1400 | 9 Mar 77 | 5600 | 8 Mar 78 a.m. | 1400 | 2 Mar 79 | 1200 |
| 7 Mar 76 | 1400 | 10 Mar 77 | 10000 | 8 Mar 78 p.m. | 2100 | 3 Mar 79 | 1200 |
| 8 Mar 76 | 2100 | 11 Mar 77 | 11800 | 9 Mar 78 | 2000 | 4 Mar 79 | 1400 |
| 9 Mar 76 | 2100 | | | 10 Mar 78 | 1800 | 5 Mar 79 | 1600 |
| 10 Mar 76 | 2100 | | | 10 Mar 78 a.m. | 1100 | 6 Mar 79 | 1600 |
| 11 Mar 76 | 2100 | | | 10 Mar 78 p.m. | 3400 | 7 Mar 79 | 1500 |
| 12 Mar 76 | 2100 | | | 11 Mar 78 a.m. | 3600 | 8 Mar 79 | 1700 |
| 13 Mar 76 | 1700 | | | 11 Mar 78 p.m. | 4100 | 9 Mar 79 | 1700 |
| 14 Mar 76 | 1700 | | | 12 Mar 78 | 4100 | 10 Mar 79 | 1700 |
| 15 Mar 76 | 1600 | | | 13 Mar 78 | 4600 | 11 Mar 79 | 1700 |
| 16 Mar 76 | 1600 | | | 14 Mar 78 | 5200 | 12 Mar 79 | 1200 |
| 17 Mar 76 | 1600 | | | 15 Mar 78 | 5200 | 13 Mar 79 | 2600 |
| | | | | | | 14 Mar 79 a.m. | 2900 |
| 18 Mar 76 | 1700 | | | 16 Mar 78 | 5600 | 14 Mar 79 p.m. | 2000 |
| 19 Mar 76 | 2200 | | | 18 Mar 78 a.m. | 5600 | 15 Mar 79 | 2000 |
| 20 Mar 76 | 2000 | | | 18 Mar 78 p.m. | 10500 | 16 Mar 79 | 1800 |
| 21 Mar 76 a.m. | 1900 | | | 19 Mar 78 | 5300 | 17 Mar 79 | 1800 |
| 21 Mar 76 p.m. | 2000 | | | 20 Mar 78 | 11600 | 18 Mar 79 | 2800 |
| 22 Mar 76 | 1800 | | | | | 19 Mar 79 | 5300 |
| 23 Mar 76 a.m. | 1600 | | | | | 20 Mar 79 | 11600 |
| 23 Mar 76 p.m. | 1800 | | | | | | |
| 24 Mar 76 a.m. | 1800 | | | | | | |
| 24 Mar 76 noon | 2900 | | | | | | |
| 24 Mar 76 p.m. | 5900 | | | | | | |
| 25 Mar 76 | 11800 | | | | | | |
| Avg. upstream location | 1570 | | 2340 | | 1990 | | 1530 |

## APPENDIX B. ESTIMATE OF ICE THICKNESS IN LITTLE RAPIDS CUT

An unconsolidated ice cover is held in position by forces from the riverbanks and a stable ice cover downstream. The natural forces that move the floating ice cover are hydraulic flow forces, wind drag, ice weight and moving ice impinging on the ice edge. Because the ice is fragmented, longitudinal (downstream) forces tend to cause it to move laterally, and this is resisted by the riverbanks. Therefore, compressive forces develop in both the lateral and the longitudinal directions; if the forces are large enough, the cover will thicken until the internal material stresses are sufficiently reduced. Under some circumstances the ice cover will also thicken from deposits of ice fragments drawn under the ice edge by water currents.

Theoretical relationships have been developed through field and laboratory research for predicting the thicknesses of unconsolidated ice covers. Researchers have found that when a river is narrow, the thickness is controlled by conditions at the ice edge. When a river is fairly wide, however, the path of compressive stresses, or arch, becomes long, and to remain stable the ice cover must become thicker than it would need to be if the river was narrower.

The river discharge at Frechette Point flows primarily through Little Rapids Cut. A small portion of the flow, however, comes down the natural channel between Island No. 1 and Sugar Island (Little Rapids). A portion of the flow that comes into the Little Rapids Cut branches off to pass between Islands No. 3, 2 and 1 (lower end). The depth varies along these alternate water routes; a rough estimate of their combined average flow area is 465 $m^2$ (5000 $ft^2$), which is a significant value. Their effect on the overall flow can only be generalized.

The discharge in Little Rapids Cut is highest just below the ferry track. Upstream of Island No. 2 some of the flow is drawn off to pass between Islands No. 2 and 3 and the mainland. At the lower end of Island No. 1 additional flow enters the Little Rapids Channel through the natural Little Rapids reach. The quantity of water entering here is probably substantially less than the water being drawn away above Island No. 2. The flow split is unknown, even under open water conditions. The effects of these parallel channels during the ice progression period are more difficult to estimate because they are ice covered by the time the period occurs.

Table B1. Data on the upper and lower sections of the Little Rapids Channel during the third week of January 1979.

| Section | Location* (ft) | Water surface elevation (ft) | Reference avg. bed elevation (ft) | Average depth (ft) | Channel width (ft) | Flow area ($ft^2$) |
|---|---|---|---|---|---|---|
| Little Rapids Cut | 48+56 | 580.28 | 548.94 | 31.34 | 757.8 | 19,319 |
| Frechette Point | 145+67 | 579.68 | 547.47 | 32.21 | 1495 | 29,133 |

* Ice boom opening is at 29+25.

Water surface elevations in Little Rapids Channel were measured in Little Rapids Cut immediately downstream of the ice boom and at Frechette Point, at the lower end of the channel. The distance between the two sites is 3,200 m (10,500 ft). The set of conditions used in the following analysis is the weekly average difference in water surface elevations between these two gauge points, or 0.18 m (0.60 ft) with a St. Marys River discharge of 1,897 $m^3/s$ (67,000 cfs) for the third week of January 1979. This stage differential is the value when the ice cover first reached Sugar Island ferry track on 20 January 1979. The slope, therefore, is $5.71 \times 10^{-5}$. Other data for this work are summarized in Table B1.

It is difficult to estimate the thickness of the unconsolidated ice cover that develops in the Little Rapids Cut because of the many variables involved. Acres American Inc. (1975) estimated that it would be between 0.9 and 1.5 m thick (3-5 ft). The method of estimation used here is patterned after Beltaos (1983), who carefully reviewed the work of several important American, Canadian and Russian researchers and developed the following relationship (Fig. B2):

$$H = h + s_i t \tag{B1}$$

where

$H$ = water level at the upstream edge of the unconsolidated ice cover

$h$ = water depth beneath the ice cover

$t$ = ice cover thickness

$s_i$ = ratio of the densities of ice and water.

He showed that the flow depth is

$$h = \left( \frac{q}{\left(\frac{4\ g\ S}{f_o}\right)^{1/2}} \right)^{2/3} \tag{B2}$$

where

$q$ = flow per unit channel width

$S$ = slope of the water surface

$g$ = gravitational constant

$f_o$ = Darcy Weisback friction factor for the ice-covered channel.

The last term is usually considered to be the average of the friction factor for ice $f_i$ and the friction factor for the riverbed $f_b$.

Beltaos assumed that the ice mass is cohesionless and determined that the ice cover thickness t is equal to

$$t = \frac{WS}{2\mu(1-s_i)} \left\{ 1 + \left[ 1 + \frac{(2\ f_o)^{1/3}\ \mu(1-s_i)}{s_i} \left(\frac{f_i}{f_o}\right) \frac{\left(\frac{q^2}{gS}\right)^{1/3}}{WS} \right]^{1/2} \right\} \tag{B3}$$

where W is the channel width and $\mu$ is the product of the angle of internal friction of the ice mass and the coefficient of lateral thrust of the accumulation. Beltaos recommended the use of $\mu$ = 1.2 and $s_i$ = 0.92.

No values of $f_o$ for the ice-covered Little Rapids Channel are available. Data were available in my files, however, for the Beauharnois Canal, which is a man-made navigation and diversion canal of similar depth for the St. Lawrence River near Montreal, Canada. Values of $f_o$ were calculated for the times when the unconsolidated ice cover first became complete in early winter on the canal; data for six years (1974-1980) were available. The values of $f_o$ varied from 0.05 to 0.07 and had an average of 0.058. The average flow velocity in the canal was 0.59 m/s (1.92 ft/s).

The Corps of Engineers hydraulics survey crew made extensive surveys of flows and flow areas at Frechette Point and at the Old North Channel (Table B2). If the Little Rapids Cut properties apply (if its flow is 69% of 1,897 $m^3/s$ [67,000 cfs] and if $f_i/f_o$ equals 1), the value of H calculated from the Beltaos equations is 10.2 m (33.6 ft), which is much higher than the actual depth of 9.54 m (31.3 ft). If one further assumes that approximately 10% of the flow passes around the small islands adjacent to Little Rapids Cut, then the calculated and the actual water elevations

Table B2. Flow distribution around Sugar Island.

| Condition | Little Rapids Channel | Old North Channel |
|---|---|---|
| Open water | 71-76% | 29-24% |
| Ice covered | 64-69% | 36-31% |

match quite well. The average flow through the cut then is 1,174 $m^3/s$ (41,470 cfs), the average velocity is 0.66 m/s (2.15 ft/s), and the estimated ice thickness is 0.88 m (2.9 ft).

This estimate accounts only for the natural effects of water currents on the unconsolidated ice cover and is the minimum thickness that one would expect to find in the Cut without shipping. The effects of icebreakers and transports could cause the ice cover to become even thicker but by an unknown amount. Based on these factors, it is assumed that the ice cover in the Little Rapids Cut is at least 0.91 m (3 ft) thick.

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